

### Remarks

This Preliminary Amendment cancels, without prejudice, claims 1-9 in the underlying PCT Application No. PCT/DE03/03801 and adds new claims 10-19.

The new claims, inter alia, conform the claims to United States Patent and Trademark Office rules and do not add any new matter to the application.

In accordance with 37 C.F.R. § 1.125(b), the Substitute Specification (including Abstract) contains no new matter. The amendments reflected in the Substitute Specification (including Abstract) are to conform the Specification and Abstract to United States Patent and Trademark Office rules or to correct informalities. As required by 37 C.F.R. §§ 1.121(b)(3)(ii) and 1.125(c), a Marked-Up Version of the Substitute Specification comparing the Specification of record and the Substitute Specification also accompanies this Preliminary Amendment. Approval and entry of the Substitute Specification (including Abstract) are respectfully requested.

The underlying PCT Application No. PCT/DE03/03801 includes an International Search Report, dated March 19, 2004, a copy of which is included. The Search Report includes a list of documents that were considered by the Examiner in the underlying PCT application.

Applicants assert that the subject matter of the present application is new, non-obvious, and useful. Prompt consideration and allowance of the application are respectfully requested.

Dated: 4/27/2005

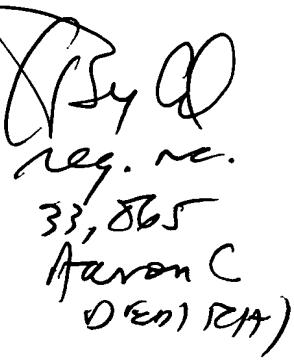
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## METHOD AND DEVICE FOR LASER DRILLING

## Specification

~~The present invention relates to a method for laser drilling according to the preamble of Claim 1, and a corresponding device according to the preamble of Claim~~

8. Background Information

5 Precision micro-holes in nozzles of fuel-injection systems are usually introduced with the aid of erosion methods. Using this technology, it is currently possible to produce minimal diameters of approximately 120  $\mu\text{m}$  in large-scale production. Furthermore, laser drilling also allows the production of precision holes having diameters of less than 120  $\mu\text{m}$ , but this has not yet been introduced as large-scale method.

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In the fuel-injection field, there is increasing demand for conical holes to the effect that a fuel-outlet orifice have a smaller diameter than a fuel-intake orifice. Such precision micro-holes are already utilized in systems for diesel fuels (direct injection) or for gasoline (manifold and direct injection).

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German Patent No. DE 199 055 71-G4 describes a laser-drilling method in which a laser beam executes a wobbling motion relative to a workpiece. This has the effect that a cone-shaped shell surface is traversed inside the workpiece. The polarization plane of the laser beam is rotated in synchrony with the wobbling motion.

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German Patent Application No. DE 100 548 53-A4 describes a method for introducing a micro-hole in a workpiece by means of a laser beam. In this case, the focus of the laser beam is moved continually along a circular path which is concentric with respect to the hole axis, the laser beam being composed of a

25 succession of short laser pulses.

In all current drilling methods, the produced bore must be subjected to follow-up treatment by hydro-erosive (HE) rounding. In fuel injection systems, for instance, this is done primarily to round the edge of the fuel intake (in addition to improving the

30 surface of the bore wall and reducing the variance among the hydraulic flow rates of the individual bore holes of a nozzle). This results in a considerable reduction of the flow resistance at this point and also reduces undesired cavitation manifestations.

MARKED-UP VERSION OF SUBSTITUTE SPECIFICATION

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An additional considerable improvement in this direction is achieved by the combination of conicalness and distinct HE-rounding.

#### Summary Of The Invention

5 The present invention is intended to selectively influence the profile of the outlet of the bore hole (fuel intake) during the drilling operation using short-pulse (ns) or ultra-short pulse (ps/fs) lasers. In particular, a simple and low-cost production of various symmetrical and asymmetrical outlet profiles is ~~to be realized~~provided, such profiles including, for instance, widened regions and bulges.

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~~This goal is achieved by a method for laser drilling having the features of Claim 1 and a corresponding device having the features of Claim 8.~~

#### Summary of the Invention

15 In the laser drilling method provided according to the present invention, a region of a component is acted upon by a laser beam and a hole is produced within this region. This action or drilling is implemented under an adjustable process-gas atmosphere. Due to reciprocal action between the utilized laser beam and the selected process gas within the area or hole acted upon by the laser beam, plasma is generated by  
20 ionization of the process gas. According to the present invention, it is additionally provided that a backing be arranged at an outlet orifice of the hole produced by the laser beam.

The process gas or gas mixture utilized according to the present invention primarily  
25 serves to increase the processing quality and to optimize the processing time, in particular to shorten the processing time. By creating special process-gas atmospheres, the laser beam - material interaction is indirectly influenced in the impinged-upon region or hole, and thus the processing process as well. The type of process-gas atmosphere determines the properties of the plasmas that forms  
30 according to the present invention during the reciprocal action of the utilized laser radiation with the material or matter to be processed, the plasma formation being aided by material vapor. A solid-state laser (Nd:YAG), for instance, is used as a laser. Different process gases in each case produce plasmas that may differ in their temperature and expansion, for instance.

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To be mentioned as a particular advantage of the method according to the present invention is the possibility of considerably reducing the process time of the HE-

rounding to produce rounded forms, or of making the HE rounding entirely unnecessary to begin with. Furthermore, using the method according to the present invention, the fuel intakes may be designed in a way that is not possible with HE-rounding. According to the present invention, it is possible, in particular, to introduce asymmetrical rounded forms or symmetrical or asymmetrical bulges right behind the fuel intake. Rounded forms have the advantage of an improved intake response, whereas bulges may be used to prevent, or also selectively generate, turbulence that may occur at the fuel intake.

Particularly important for the selective design of the outlet is the plasma state shortly before and during the reemergence of the laser beam from the material. Depending on the selected parameters such as gas composition, gas pressure and/or gas flow direction, rounded forms, bulges and/or sharp discharge edges may form; these phenomena may occur across the entire bore-hole outlet in an even, rotationally symmetrical manner, or they may come about on one side only.

Rear-space protection materials, so-called backings, are used to prevent the free propagation of the laser beam after it reemerges from the material or matter. This may normally be utilized to prevent damage to another workpiece or component, or areas of the same workpiece. Furthermore, such backings are able to maintain the state of a closed bore hole for a certain period of time and thus contribute to the production of a desired discharge orifice or a bore hole outlet.

Depending on the application, backings are made from various materials such as polymers, metals or ceramic materials.

A backing is able to influence the formation of a bore hole outlet by reflecting the arriving laser radiation back in the material direction or in that it influences the plasma, ionized from the process gas, in its propagation, thereby leading to additional material removal. An additional effect may come from a plasma that is possibly produced by erosion of the backing.

~~Advantageous embodiments of the method according to the present invention and the device according to the present invention are the subject matter of the dependent claims.~~

For practical purposes, the method uses as process gas an inert gas such as nitrogen, in particular with the addition of noble gases such as helium, argon and the

like. The use of such a process gas has the advantage that an area to be acted upon is rendered inert, thereby preventing oxidation of this region. Moreover, such a composition of the process gas ensures adequate surface qualities of the bore hole wall and melt-film thicknesses.

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Furthermore, the process gas is preferably pressurized, the pressure being preferably set to below approximately 1.5 bar. This promotes the formation of hollow forms in the produced holes. It is also possible to select higher pressures, which allows hollow forms to be suppressed. Overall it may be said that the pressures utilized according to the present invention result in hollow forms in the vicinity of the edge region of the workpiece to be processed. The higher the pressure utilized, the greater the shift of a hollow form toward the interior of the workpiece.

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Furthermore, it may preferably be provided to set the impingement direction of the process gas by tilting relative to the direction of the laser beam, the tilting angle possibly amounting to between 0° and 15°. Suitable selection of a tilting angle ensures that hole shapes, in particular hollow forms or widened forms, with various degrees of asymmetry are able to be formed.

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Due to the plasmas produced in implementing the method according to the present invention, calculated pressures on the order of a few 100 bar and flow velocities of several 10 km/s may occur in the acted-upon region or hole. Due to an accelerated removal of a melt resulting therefrom, among others, an active contribution is rendered towards higher material removal.

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Apart from the prevailing introduction conditions of the process gas (composition, pressure, direction), the ionization of the process gas may also be influenced by, in particular, the properties of the laser beam such as wavelength and output.

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A backing used in this context may exhibit thermal or optical characteristics that influence the shape or the design of the outlet orifice. Suitable metallic materials, especially copper, are to be provided here, in particular. These material properties are especially important for the degree of the widening of the outlet orifice. For example, when using laser wavelengths of 1064 µm and a backing of copper which

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is arranged at a suitable distance from the outlet orifice, relatively large widened forms are produced, whereas relatively small widened forms come about with a backing of steel. Furthermore, the geometry of the backing may influence the form or design of the outlet orifice. In the present invention, the use of copper as backing

material is particularly preferred. It should be mentioned that copper is generally not favored in engine building since sulfide may form in the case of copper deposits in the engine area due to reciprocal actions with sulfide that is present in the fuel, such sulfide formation having a negative influence on the service life of the engine.

5 However, these disadvantages are clearly outweighed by the properties of copper that are able to be utilized within the framework of the present invention in connection with the production of specially formed holes in workpieces.

10 Furthermore, it may preferably be provided to arrange the backing at a distance from the outlet opening that influences the shape of the outlet orifice. Such a distance is preferably selected between 20  $\mu\text{m}$  to 200  $\mu\text{m}$ .

15 By appropriate selection of such a distance, the geometry of the widened form of the borehole exit may be influenced in a simple manner.

The backing may be arranged at a specified angle by tilting relative to the outlet orifice. Various degrees of tilting produce widened areas of the outlet hole of the borehole whose asymmetries vary accordingly. The angles preferably used for this purpose are in the range of  $0^\circ$  to  $20^\circ$ .

20 Especially by suitable selection of the form of the backing or the arrangement of the backing relative to the outlet orifice, symmetrical or asymmetrical rounded forms are able to be introduced in a region of the outlet orifice of a hole in an uncomplicated manner, yielding the advantage of no longer requiring retroactive HE rounding at all or requiring such rounding only to a limited degree.

30 The device according to the present invention by which the method of the present invention, in particular, is able to be implemented, is distinguished by the provision of a laser beam, a retaining device for a component to be processed and means for adjusting a process-gas atmosphere.

35 At least one gas nozzle may preferably be provided as means for adjusting the process-gas atmosphere. In this way, flowing process gas of a suitable composition may be aimed at the region of a workpiece to be acted upon in a manner that is easy to control or regulate and may be carried out at a suitable pressure and an appropriate angle. A suitable composition of the process gas may be provided by a gas mixer.

According to the present invention, the device may additionally be refined in such a way that a backing is able to be positioned at an outlet orifice produced in the component by the action of the laser beam.

## 5 Brief Description of the DrawingOf The Drawings

~~The present invention is now described in greater detail on the basis of the enclosed drawing.~~

~~The figures in these drawings show:——~~

- 10 Figure 1 shows a schematic representation of a preferred specific embodiment of the device according to the present invention for implementing the laser-drilling method according to the present invention;\_

- 15 Figure 2 shows a detail of the device according to Figure 1, in an enlarged representation;\_

~~Figure~~Figures 3a through Figure 3e show schematic representations of boreholes produced according to the present invention, in a lateral sectional view;\_and\_

- 20 Figures 4a through 4c show schematic representations of boreholes produced according to the present invention, in a lateral sectional view or in a plan view on the basis of electron-microscopic photographs.

## Detailed Description

- 25 The illustrated specific embodiment of the device according to the present invention is designated as a whole by 100. A laser beam 30 generated by a laser 31 first traverses an expanding lens 32. Laser beam 30 is partially reflected or switched at a shutter 34, scattered or excess residual radiation being absorbed by a radiation sink 33. The direction of laser beam 30 inside its optical path is deflected by one or a
- 30 plurality of mirrors 37. A trepanning lens 35 is also disposed inside the optical path, and the device for focusing the laser beam also has a focusing lens 36. In addition, the optical path of laser beam 30 runs through a gas nozzle 12 and impinges upon a workpiece 40 to be processed.

- 35 The process gas required to implement the method according to the present invention is provided by a gas mixer 11 and forwarded to a gas nozzle 12 via a line 11a. The process gas is blown directly onto workpiece 40 with the aid of a gas nozzle 12.

Workpiece 40 is mounted in a handling device 50. Using suitable measures, this handling device 50 is moveable in all three spatial directions x, y and z, so that a suitable position of workpiece 40 for implementing the method is able to be adjusted.

5 Positioning the focusing lens 36 along axis z allows laser beam 30 to be varied in its focusing position. It is likewise possible to position gas nozzle 12 with respect to the direction of the optical path of laser beam 30 running through gas nozzle 12, or to position it relative to workpiece 40. In the process, a movement along direction x or y takes place. A rotation of gas nozzle 12 is also able to be realized by means of a  
10 suitable mechanism, such rotatability being symbolized by  $\phi$  in Figure 1.

The method for laser drilling according to the present invention is able to be realized in a very simple manner when using this specific embodiment of device 100 according to the present invention. Laser beam 30, its optical path having traversed  
15 gas nozzle 12, impinges upon workpiece 40 within a region to be acted upon. A selected or adjusted process gas, provided by gas mixer 11, flows under pressure from an adjustable direction out of nozzle 12 onto the region of workpiece 40 to be acted upon. This, in particular, promotes the ionization of process gas to plasma by reciprocal action between process gas and laser beam 30 within the acted-upon  
20 region.

Figure 2 shows a cut-away portion of Figure 1. Using a mounting support 51 workpiece 40 is able to be firmly positioned with respect to handling device 50, a suitable position of workpiece 40 relative to handling device 50 being adjustable by  
25 means of movement via mounting support 51. In the same way, a backing 20 is able to be firmly positioned relative to handling device 50 via a holding device 52, a suitable position of backing 20 relative to handling device 50 being adjustable via holding device 52 by movement. By controlling mounting support 51 or 52, backing 20 and workpiece 40 may be spatially positioned as desired with respect to each  
30 other; this may be done both before and also during the described method.

A hole 44 to be produced in workpiece 40 by means of the laser-drilling method is created in the location of workpiece 40 where laser beam 30 impinges upon workpiece 40 or acts upon it, the laser beam exiting at an outlet opening 43 of hole  
35 44 on the side of workpiece 40 that faces backing 20. The process gas, which is blown by a gas nozzle (not shown) onto workpiece 40 at a suitable angle and from an appropriate distance, is ionized to plasma by reciprocal action with laser beam 30 in the region of hole 44 or a region of outlet opening 43.



This produces selective geometrical forms in the region of hole 44 or outlet opening 43 as will now be illustrated by way of example with the aid of the following figures.

5     Figures 3a through 3e show detailed views of holes or bore holes 44 within  
workpiece 40 in a sectional view in parallel with a bore hole center axis 46 of hole  
44. A laser beam 30 (not shown) had been aimed at workpiece 40 from the left, in  
parallel with bore-hole center axis 46; laser beam 30 penetrated workpiece 40 in the  
impingement region, the entrance location not being shown in Figures 3a to 3e. The  
10    individual outlet openings 43 of holes 44 are visible in Figures 3a to 3e.

In Figure 3a, a region of outlet opening 43 of bore hole 44 has a symmetrical  
widened form 41 or rounded form, which is the result of a preferably symmetrical  
arrangement of a backing (not shown) with respect to bore-hole center axis 46 within  
15    a region behind - in the illustration of Figures 3a to 3e, to the right - of outlet opening  
43. The degree of this widened form 41 or rounding is able to be influenced by  
appropriate spacing of the backing relative to outlet opening 43.

Widened form 41 of an area of outlet opening 43 of bore hole 44 shown in Figure 3b  
20    has an asymmetrical design or is rounded on one side only. In this example the  
method according to the present invention was implemented in such a way that the  
backing was arranged in a region behind outlet opening 43 and tilted at a suitable  
angle with respect to bore hole center axis 46.

25    Bore hole 44 from Figure 3c has symmetrical or bilateral bulges 42 in a region of  
outlet opening 43 of hole 44. Such a bulge 42 is realizable by the described  
reciprocal action between laser beam and formed plasma, for example.

Bore hole 44 shown in Figure 3d has an asymmetrical bulge 42. Such an  
30    asymmetrical form of bulge 42 is facilitated by tilting of a nozzle that introduces the  
process gas, such tilting being implemented at a suitable angle relative to bore hole  
center axis 46 or the laser beam.

Bore hole 44 in Figure 3e is designed such that ~~is it~~ has a combination of widened  
35    form 41 and bulge 42 in a region of outlet opening 43. Such a design may be  
realized by combining the afore-described measures (tilting of the backing and  
impingement of the process gas at an angle).

Additional specific embodiments of holes 44 or outlet openings 43 within workpiece 40 produced by the method according to the present invention are shown in Figures 4a to 4c in longitudinal section or in a plan view.

5 Figure 4a shows two different forms of bulges 42 in longitudinal section.

Furthermore, intake openings 45 are shown, which are produced by impingement of the workpiece by a laser beam arriving from the left, and have a smaller diameter than outlet openings 43 on the right. In hole 44a shown above, bulge 42 is  
10 asymmetrical, analogously to Figure 3d, whereas two symmetrical bulges 42 are shown in lower hole 44b, analogously to Figure 3c.

Outlet opening 43 illustrated in Figure 4b has an asymmetrical widened form 41 or rounding. This ~~was~~is realized by appropriate measures as they have been described  
15 with reference to Figure 3b. Figure 4c shows an outlet opening 43 from the same perspective as Figure 4b, this opening having a symmetrical widened form 41 or rounding, which is realized by analogous implementation of the method according to the present invention as it was described with reference to Figure 3a.

Abstract Of The Disclosure**Summary**

5 A method and device for laser drilling in which the geometric form of the drill-hole wall is influenced by reciprocal action between a laser beam and a supplied process gas, which thereby is ionized to plasma. Furthermore, the outlet opening of the drill hole is influenced by a suitable arrangement of a backing.